Method for increasing efficiency of thermotunnel devices

Technical Field

This invention relates to thermotunneling and thermionic devices.

Background Art

5   Simple thermotunnel device comprising two metallic electrodes separated by vacuum gap has energy diagram shown in Figure 1 (image charge modification of the barrier shape is omitted for simplicity). 10 and 12 are metallic electrodes separated by a distance d_0 in a vacuum (U.S. Patent No. 6,417,060;
10   WO99/13562). The cooling power and efficiency of such devices have been calculated by Hishinuma et al. [Appl. Phys. Letters (2001) 78(17):2572-2574], who show that that electrons having a wide spectrum of energies take part in heat pumping. Thus, both electrons 14 sitting at low energy levels (around the Fermi level, f_e) and electrons sitting at higher energy levels 16 take
15   part in tunneling through the potential barrier and transfer heat from electrode 10 to electrode 12 (see Figure 1; for simplicity it is assumed that work functions, Φ, of two electrodes are equal and equal to applied voltage eVbias). Tunneling of low energy electrons leads to low efficiency heat pumping. Pumping of low energy electron requires the same work from external
20   source as pumping of high energy electron (eV$_{bias}$ in both cases). At the same time low energy electrons remove less heat from the emitter than high energy electron. Besides that in some cases tunneling of low energy elelctron might cause negative heat flow.

Disclosure of Invention

25   From the foregoing, it may be appreciated that a need has arisen for a means for shifting to higher energies the spectrum of energies of electrons that are involved in tunneling.

The present invention comprises a tunneling device in which the collector electrode is modified so that tunneling of higher energy electrons from the
30   emitter electrode to the collector electrode is enhanced.

In one embodiment, the collector electrode is in contact with an insulator layer disposed between the collector and emitter electrodes.

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The present invention additionally comprises a method for enhancing tunneling of higher energy electrons from an emitter electrode to a collector electrode, the method comprising the step of contacting the collector electrode with an insulator, and placing the insulator between the collector
5   electrode and the emitter electrode.

The present invention additionally comprises a method for cooling comprising applying a bias voltage to an emitter electrode; placing a collector electrode a distance d_0 from the emitter electrode; placing an insulator layer a distance d_1 from the emitter electrode; and contacting the insulator
10   layer and the collector layer, whereby electrons tunneling from the emitter electrode to the collector electrode and the emitter electrode, thereby cooling the emitter electrode.

Brief Description of Drawings

For a more complete explanation of the present invention and the technical
15   advantages thereof, reference is now made to the following description and the accompanying drawing in which:

Figure 1 is a diagrammatic representation of energy levels in prior art tunneling devices.

Figure 2 is a diagrammatic representation of prior art tunneling devices
20   (Figure 2a) and a tunneling device of the present invention (Figure 2b).

Figure 3 is a diagrammatic representation of potential energy-distance profiles for prior art tunneling devices (Figure 3a) and a tunneling device of the present invention (Figure 3b).

Best Mode for Carrying Out the Invention

25   Embodiments of the present invention and their technical advantages may be better understood by referring to Figures 2 and 3.

It is well known that when an electric field E is applied to an insulator it causes polarization of the insulator atoms and the resulting field is decreased inside the insulator. Thus the field inside the insulator, E_1 is
30   equal to E/ε, where ε is the dielectric constant of the insulator.

Referring now to Figure 2a, which shows a prior art tunneling device, an emitter electrode 22 and a collector electrode 24 are separated by a vacuum gap. Upon application of an external voltage 20, V_{bias}, the field in the vacuum area between the electrodes is E.

Referring now to Figure **3a**, which shows the relationship between potential energy **E** and electrode separation **X** for the two electrodes of Figure **2a**, high energy electrons **32** and low energy electrons **34** are able to tunnel across the energy barrier. The high energy electrons have to overcome a thinner barrier

5   than the low energy electrons, but the lower energy levels around the Fermi level are much more highly populated than the higher energy levels, and thus the efficiency of heat pumping is low, as discussed above.

Referring now to Figure **2b**, which shows a tunneling device of the present invention, in addition to electrodes **22** and **24**, an insulator **28** is placed

10   between the electrodes and attached to the collector electrode. This creates a field E_1 inside the insulator layer and field E_2 in the vacuum between the insulator and metallic electrode. The field inside the insulator will therefore decrease and the field in vacuum gap between the insulator and metallic electrode will increase, and thus $E_2 > E > E_1$.

15   Referring now to Figure **3b**, which shows the relationship between potential energy **E** and electrode separation **X** for the two electrodes of Figure **2b**, high energy electrons **32** and low energy electrons **34** are able to tunnel across the energy barrier as in Figure **3a**. Now, however, when the same V_{bias} is applied, the relationship between energy and distance has two slopes: in the range 0 −

20   d_1, the slope corresponds to field E_2 in the vacuum between the insulator and emitter electrode, and in the range $d_1 - d_0$ the slope corresponds to the field E_1 inside the insulator. It is obvious that now the high energy electrons of Figure **3b** have to overcome a thinner barrier than electrons with the same energy in Figure **3a**, while at the same time tunneling conditions for

25   low energy electrons remain approximately the same (compare Figures **3a** and **3b**). In this way, for the electrode arrangement of Figure **2b**, the energy spectrum of the tunneling electrons will shift in the direction of higher energies, which will in turn dramatically increase COP (Coefficient of Performance or useful cooling power).

30   A further advantage of the present invention is that the insulator layer prevents electrodes from shorting. Electrodes having large areas of surfaces tend to touch each other in some places, which cause local electric short circuits and damage the surfaces of the electrodes. The insulator layer prevents electrodes this, and therefore the device has lower requirements on

35   electrode surface flatness and is easier to make.

The following is given by way of example to illustrate the present invention, and is not intended to limit the scope of the present invention. Referring again to Figure **2b**, which shows a tunneling device of the present invention,

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an emitter electrode 22 and a collector 24 are separated by a distance d_0 of 150Å, and an insulator layer 28 of thickness $d_0 - d_1$ of 120Å, and the gap between insulator layer 28 and emitter 22 d_1 is 30Å. In a preferred embodiment, the insulator layer is a metal oxide. In a particularly preferred

5   embodiment the insulator layer is aluminum oxide. Field E created by bias voltage 20, V_{bias}, is applied across the device. For aluminum oxide, the dielectric constant is about 10, which means that in the first approximation field E_2 could be neglected. Consequently the entire field will be concentrated inside thin 30Å vacuum layer between insulator and metal

10 electrode. The applied voltage, V_{bias}, may be therefore be reduced to a approximately a fifth of the value utilized in the absence of the insulator layer to achieve the same field strength.

Furthermore, Hishinuma et al. calculate useful cooling coefficient or COP values for a range of inter-electrode spacing and electrode work functions,

15 and show that COP is inversely proportional to the applied voltage (V_{bias}). Thus for the example above the bias voltage could be over four times lower to get the same cooling power. Because COP is inversely proportional to V_{bias} it will result in approximately 5 times increase of COP. In reality COP will increase more than that because of filtering effect of potential barrier.

20 While this invention has been described with reference to specific embodiments, it is to be understood that this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments will be apparent to persons skilled in the art upon reference to this description. It is to be further understood,

25 therefore, that numerous changes in the details of the embodiments of the present invention and additional embodiments of the present invention will be apparent to, and may be made by, persons of ordinary skill in the art having reference to this description.

For example, particular values for the separation of the electrodes, the

30 thickness of the insulator, and the distance between the insulator and the emitter are given in the foregoing. Other values may be used without departing from the scope of the present invention. Thus the distance between the electrodes may be in the range of 10 - 200Å, and the distance between the emitter and the insulator layer may be in the range of 5 - 50Å.

35 Specific methods for the fabrication of devices of the present invention have not been given as there are a number of approaches that may be used by one of ordinary skill in the art to achieve the objectives of the present invention. Thus the devices may be fabricated by attaching a pre-formed insulator layer

to the collector electrode, or the insulator layer may be deposited onto the collector electrode. For example, a layer of aluminum oxide may be deposited onto the surface of the collector by reactive DC magnetron sputtering of aluminum in the presence of oxygen.

5   ## Industrial Applicability

Thermotunneling devices of the present invention may be used for cooling applications, in which case the emitter electrode is in thermal contact with a heat source, and the collector electrode is in contact with a heat sink.

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